E 1.28: SOLAR / 2009 - 79 / 14 Alepk 1214323

SOLAR/2009-79/14

Solar Energy System Performance Evaluation

RADEMAKER CORPORATION
OFFICE AND WAREHOUSE BUILDING
Louisville, Kentucky
October, 1978 through March, 1979

U.S. Department of Energy

National Solar Heating and Cooling Demonstration Program

National Solar Data Program

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Availabie from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $6.00
Microfiche $3.00

SOLAR/2009-79/14
Distribution Category UC-59

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

RADEMAKER CORPORATION
OFFICE/WAREHOUSE
LOUISVILLE, KENTUCKY

OCTOBER 1978 THROUGH MARCH 1979

RICHARD V. WALKER, PRINCIPAL AUTHOR
WILLIAM H. McCUMBER, MANAGER OF PERFORMANCE ANALYSIS
LARRY J. MURPHY, IBM PROGRAM MANAGER

IBM CORPORATION
150 SPARKMAN DRIVE
HUNTSVILLE, ALABAMA 35809

PREPARED FOR THE
DEPARTMENT OF ENERGY
OFFICE OF ASSISTANT
SECRETARY FOR
CONSERVATION AND SOLAR APPLICATIONS
UNDER CONTRACT EG-77-C-01-4049
H. JACKSON HALE, PROGRAM MANAGER

TABLE OF CONTENTS

SECTION	TITLE	PAGE
1.	FOREWORD	1
2.	SUMMARY AND CONCLUSIONS	3
3.	SYSTEM DESCRIPTION	9
4.	PERFORMANCE EVALUATION TECHNIQUES	13
5.	PERFORMANCE ASSESSMENT	15
	5.1 Weather Conditions	16
	5.2 System Thermal Performance	19
	5.3 Subsystem Performance	27
	5.3.1 Collector Array Subsystem	28
	5.3.2 Storage Subsystem	39
	5.3.3 Hot Water Subsystem	46
	5.3.4 Space Heating Subsystem	48
	5.4 Operating Energy	53
	5.5 Energy Savings	56
6.	REFERENCES	59
APPENDIX A	DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS	A-1
APPENDIX B	SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR THE RADEMAKER CORPORATION SITE	B-1
APPENDIX C	LONG-TERM AVERAGE WEATHER CONDITIONS	C-1

LIST OF FIGURES AND TABLES

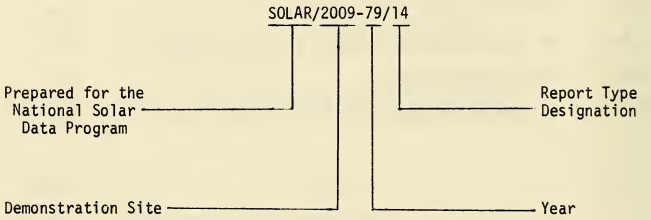
FIGURE	TITLE	PAGE
3-1	Rademaker Corporation Solar Energy System Schematic	10
5.3.1-1	Collector Array Operating Point Histogram and Instantaneous Efficiency Curves, Liquid System.	35
5.3.1-2	Collector Array Operating Point Histogram and Instantaneous Efficiency Curves, Air System.	36

TABLE	TITLE	PAGE
5.1-1	Liquid System Weather Conditions.	17
5.1-2	Air System Weather Conditions	18
5.2-1	Combined System Thermal Performance	20
5.2-2	Liquid System Thermal Performance	21
5.2-3	Air System Thermal Performance	22
5.2-4	Combined Solar Energy System Coefficients of Performance	23
5.2-5	Liquid Solar Energy System Coefficients of Performance	24
5.2-6	Air Solar Energy System Coefficients of Performance	25
5.3.1-1	Liquid System Collector Array Performance	29
5.3.1-2	Air System Collector Array Performance	30
5.3.1-3	Liquid System Energy Gain Comparison	32
5.3.1-4	Air System Energy Gain Comparison	33
5.3.2-1	Liquid System Storage Subsystem Performance	41
5.3.2-2	Air System Storage Subsystem Performance.	42
5.3.2-3	Air System Auxiliary Storage Subsystem Performance.	43

FIGURE	TITLE	PAGE
5.3.3-1	Hot Water Subsystem Performance	47
5.3.4-1	Liquid Heating Subsystem Performance	49
5.3.4-2	Air Heating Subsystem Performance	50
5.3.4-3	Mode Duration	52
5.4-1	Liquid System Operating Energy	54
5.4-2	Air System Operating Energy	55
5.5-1	Liquid Energy Savings	57
5.5.2	Air Energy Savings	58

NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the Rademaker Corporation project site is designated as SOLAR/2009-79/14. The elements of this designation are explained in the following illustration.



- Demonstration Site Number:

  Each Project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

- Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).

  - Solar Energy System Performance Evaluations are designated by the number 14.

  - Solar Project Descriptions are designated by the number 50.

  - Solar Project Cost Reports are designated by the number 60.

These reports are disseminated through the U.S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth in order to achieve a substantial reduction in non-renewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the System Performance Evaluation Report, is published on a regular basis. Each parameter

presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network.

All reports issued by the National Solar Data Program for the Rademaker Corporation solar energy system are listed in Section 6, References.

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Rademaker Corporation solar energy system. The analysis covers operation of the system from October 1978 through March 1979. The Rademaker Corporation solar energy system provides space heating and domestic hot water for a 10,000 square foot office and warehouse building in Louisville, Kentucky. A detailed system description is contained in Section 3. Analysis of the system thermal performance was accomplished using a system energy balance technique described in Section 4. Section 2 presents a summary of the results and conclusions obtained while Section 5 presents a detailed assessment of the system thermal performance.

Acknowledgements are extended to Mr. Richard Rademaker and his staff. Their insight and cooperation in the resolution of various on-site problems during the reporting period were invaluable.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report provides an operational summary of the solar energy system installed at Rademaker, an office/warehouse located in Louisville, Kentucky. This analysis is conducted by evaluation of measured system performance and by comparison of measured weather data with long-term average climatic conditions. The performance of major subsystems is also presented. The Rademaker Corporation Solar System has both a liquid solar collector array and distribution system and an air collector array and distribution system. Both systems exchange collected energy to the conditioned space by a common forced air system which is basically the heating system which was in place prior to the solar system retrofit. The liquid and air systems will be individually treated and their combined performance discussed in summary.

The measurement data were collected [References 7-12]* by the National Solar Data Network (NSDN) [1] for the period October 1978 through March 1979. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report.

Features of this report include: a system description, a review of actual system performance during the report period, analysis of performance based on evaluation of meteorological load and operational conditions, and an overall discussion of results.

---

* Numbers in brackets designate References found in Section 6.

Monthly values of average daily insolation and average outdoor ambient temperature measured at the Rademaker site are presented in Tables 5.1-1 and 5.1-2. Also presented in the tables are the long-term, average monthly values for these climatic parameters.

The design objective of the Rademaker Corporation solar energy system was to make possible a true comparison of a liquid and an air system, working side by side, under exactly the same operating conditions. This presumed that both systems would give nominal performance over the heating season. It will be shown that for this reporting period the solar energy delivered to the space heating load was very close to being equal for the liquid and the air systems. The characteristics of that delivery were markedly different and serve to highlight the advantages and disadvantages of each system.

Both systems began space heating on October 5, 1978 and contributed to the space heating load through March 1979. By November 11, 1978 and through January 25, 1979 the liquid system contributed a negligible amount of energy to the heating load because the stored energy could not be extracted. The liquid transfer pump and coupling had failed and the water level in the storage tank had been allowed to reach an unacceptably low level.

The air system exhibited two undesireable characteristics from the outset. The controller cycled (stuttering operation) the air flow through the collectors under intermittent insolation. Motorized dampers leaked when in their closed positions and the controlled routing of the solar heated air was not as expected. When heated air was intended to go exclusively to the rock storage, it would also find its way into the office area and back to the collectors through a spurious routing. Early in the heating season, when the insolation was still high and there was no heating demand during the office working hours, the losses caused an over temperature condition in the controlled space. The action taken at that time was to simply disable the solar operation on mild days.

By late January, the liquid system was working normally and was characterized by energy storage during the day and energy delivery to the heating load at night. The direct path (by-passing storage) was inhibited for the entire reporting period. Selected motorized dampers were replaced in the air system in mid-November and as the result of a new control sequence the motorized damper controlling solar heated air to the perimeter zone opened upon heating demand whether or not the solar system was able to provide usable energy for space heating. This created a spurious path through the office back to the collector array and both solar and auxiliary energy were then inadvertently dissipated from the collectors to the outside environment. An additional loss path allowed solar energy to be released into the warehouse area. This no doubt was useful in keeping the warehouse warmer than it would have been as a planned uncontrolled area. However, the space heating load identified in this report is only controlled energy as directly measured with the normal delivery system. As an example, in the month of February, a total of 1.66 million Btu of thermal energy was uncontrolled. Approximately 0.64 million Btu were lost through the collector array, 0.88 million Btu was lost to the warehouse, and 0.17 million Btu were recaptured by the rock storage. In general, the air system complemented the liquid system. The air system delivered eight times as much collected energy directly to the space heating load as the liquid system and delivered the energy predominately during the day. Conversely, the liquid system delivered its energy at night and the contribution was almost entirely from storage.

Subjective observations, based on an overview of the measured performance and the inefficiencies introduced by prolonged malfunctioning of selected components of both the liquid and air systems, are as follows:

- The temperatures of the liquid storage tanks are low and suggest that a higher ratio of collector area to storage volume be considered in future designs.

- The auxiliary air storage (158 cubic feet of rock), as installed and ducted, is of negligible benefit and should be eliminated from the system.

- The above-the-floor air storage (78 cubic feet of rock) carried the storage to space heating load. Its utility in a liquid-air combined system should be compared on a cost basis with liquid storage only (optimally sized). If the leaking damper problems cannot be solved by retrofit, elimination of air storage and the normal control of motorized damper D1 should improve overall performance.

The following specific performance is cited from supporting tables given in following sections.

Weather conditions were generally as expected with respect to the long-term projections with the exception of average monthly temperatures that were seven degrees below normal in January and February.

Since a dual-system is used, the method for reporting the data will be as follows: total or average (liquid system parameter/air system parameter). The liquid and air systems provided 63.07 (33.51/29.56) million Btu of thermal energy to the domestic hot water and heating loads. The solar energy collected was 20.75 (13.94/6.81) million Btu and the solar energy used for load support was 12.63 (7.09/5.54) million Btu. By comparison, the expected solar energy used was 20.70 (10.70/10.00) million Btu. The most descriptive parameters for overall performance are the solar fractions, which were 20 (21/19) and 33 (32/34) percent, measured and expected, respectively.

The coefficient of performance (COP) factor shows the effect of reduced energy or of excessive operating energy for the amount of energy being transported since the COP is the ratio of solar energy to the electrical energy required for solar energy system operation. The solar energy system COP was 0.95 (2.14/0.62), the collector array subsystem COP was 11.02 (20.49/5.67), and the space heating subsystem COP was 0.88 (1.36/0.72).

The collector arrays collected 20.75 (13.94/6.81) million Btu of the 78.81 (44.92/33.89) million Btu of incident energy available for an array efficiency of 25.5 (31/20) percent. The efficiency is improved when the

collected energy is compared to the incident energy which is available during active collector pump/blower operation. For the same collection, and 66.58 (38.63/27.95) million Btu of operational incident energy, the operational collector efficiency was 30 (36/24) percent.

The liquid storage subsystem performance was significantly reduced because of the almost total cut off of energy from the storage tank for several months. Energy was simply lost to the warehouse ambient environment. The resultant efficiency was 34 percent. The air system auxiliary storage was totally ineffectual. The main air system storage subsystem performance suffered badly from spurious routing of delivered air due to leaking dampers and had an average efficiency of only 16 percent.

The domestic hot water subsystem was instrumented only to the extent that the energy difference between collection and storage in the liquid system was allocated to the hot water load. In monthly reporting, the solar energy to the domestic hot water subsystem was not included in the load performance. In this analysis the hot water load of 3.32 million Btu was included as a part of the heating load for the convenience of deriving the total system expected solar fraction and expected system thermal performance, and was also used directly in the calculation of fossil savings.

The space heating load was 59.72 (30.16/29.56) million Btu, of which solar energy supplied 9.30 (3.76/5.54) million Btu for a measured solar fraction of 15.5 (12/19) percent. The performance was below expectation and in large part caused by the losses experienced.

The operating energy was 13.44 (4.42/9.02) million Btu. The air system used 1.20 million Btu of electrical energy to collect 6.81 million Btu of solar energy whereas the liquid system used 0.68 million Btu of electrical energy to collect 13.94 million Btu of solar energy. In part, the air system is penalized because almost half of the electrical energy used by the collector blower, although allocated to the collection function, also delivers solar energy directly to the load. In the liquid system, the collector operating energy is used exclusively to deliver solar energy to storage and not to the load.

Energy savings are expressed as fossil savings (natural gas) and electrical savings (negative of operating energy). The fossil savings were 21.07 (11.83/9.24) million Btu and the electrical savings were -10.77 (-3.05/-7.72) million Btu. If one were to simply add the fossil and the electrical savings on the basis of energy in Btu, the net savings would be 10.70 million Btu. However, since electrical energy has between two and three times the cost of natural gas for the same Btu equivalency, no savings were realized on the basis of dollars. Again, it should be pointed out that both the air and the liquid systems had anomalous operation and no apparent effort was made to keep the two systems operating at the same time to carry out the stated design objective of making a running comparison of performance.

3. SYSTEM DESCRIPTION

The solar energy heating system at Rademaker Corporation is designed to provide 50 percent of the space heating and 50 percent of the domestic hot water preheating for a 10,000 square foot office and warehouse building in Louisville, Kentucky. The solar installation, by design, consists of two separate solar energy systems. One system utilizes liquid as the energy transfer medium; the other system utilizes air as the transfer medium. The purpose of separate solar energy systems was to evaluate the merits of each system in meeting a common space heating load. The two solar heating systems are shown schematically in Figure 3-1.

The liquid system has an array of six flat-plate collectors manufactured by Solar Development, Inc., with a gross area of 240 square feet. The array faces south at an angle of 53 degrees from the horizontal. A solution of 46 percent propylene glycol and 54 percent water is employed as a heat transfer medium. Solar energy is stored in a 560-gallon thermal storage tank located in the warehouse. Solar energy is transferred to meet the space heating demand by two methods. In the first method, solar heated hot water is circulated on demand, from water thermal storage to heat exchangers HX2 and HX3 in the supply ducts of the drafting room and perimeter zone, respectively. In the second method, the glycol-water solution in the collection loop is directed, on demand, to heat exchanger HX4 in the supply duct of the perimeter zone. Circulation fans F2 and F3 distribute the solar energy to meet the space heating loads. Energy is also distributed to a domestic hot water heat exchanger that extracts solar energy from the glycol-water solution to preheat domestic hot water in the building. (The hot water load is small, and is not instrumented.)

The air system has an array of 10 flat-plate collectors manufactured by Solaron Corporation with a gross area of 195 square feet. The array faces south at an angle of 33 degrees from the horizontal. Solar energy is stored in two

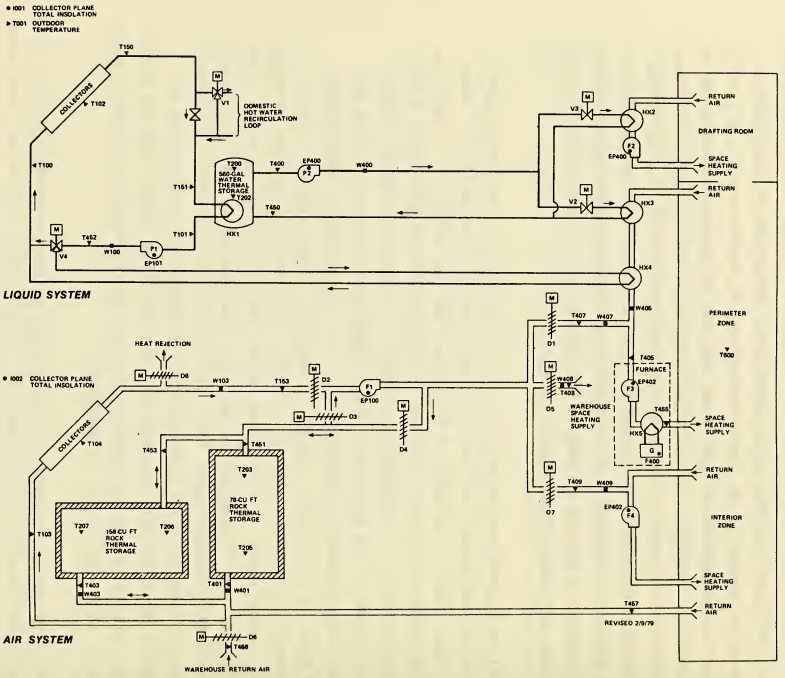


Figure 3-1. RADEMAKER CORPORATION SOLAR ENERGY SYSTEM SCHEMATIC

rock thermal storage units in the warehouse which contain a total of 236 cubic feet of crushed rock. Solar energy is transferred to meet the perimeter, warehouse, and interior zone space heating demands using circulation fan F1. Circulation fans F3 and F4 distribute energy to the perimeter and interior zones, respectively. Solar heated air can be distributed directly from the collectors, or from rock thermal storage to meet the space heating loads. The solar energy control system determines which space heating load receives solar energy when a demand exists. The solar space heating load priorities are: first, interior zone heating; second, perimeter zone heating; and third, warehouse heating.

Solar energy from the liquid system is mixed with solar heated air from the air system and distributed to the perimeter zone using circulation fan F3. When solar energy is inadequate to provide perimeter zone space heating, auxiliary thermal energy is supplied by a natural-gas furnace.

The liquid system has four modes of operation.

Mode 1 - Collector-to-Storage: This mode is entered when the difference between the collector outlet temperature and the water thermal storage temperature is greater than 14°F. Pump P1 circulates the liquid through the collectors, then to storage heat exchanger HX1 and returns to the collectors. Circulation continues in this mode until the temperature difference between the collector outlet and storage is less than 4°F.

Mode 2 - Storage-to-Conditioned Space: This mode is entered when two conditions are satisfied: first, a demand for space heating exists; secondly, the temperature of the storage water is above 85°F. Water is circulated from storage to heat exchangers HX2 and HX3 located in the supply ducts of the drafting room and perimeter zone. Air circulation fans F2 and F3 distribute the solar energy to the space heating zones. This mode continues until the storage temperature is below 85°F or the demand for space heating is satisfied.

Mode 3 - Collector-to-Conditioned Space: This mode is entered when two conditions are satisfied: first, the temperature of the liquid at the outlet side of heat exchanger HX1 is greater than 120°F; secondly, there is a demand for space heating from the perimeter zone. Solar energy is directed by valve V4 to heat exchanger HX4 in the supply duct of the perimeter zone. Fan F3 distributes the solar energy to the perimeter zone. Circulation continues in this mode until the temperature at outlet of heat exchanger HX1 is less than 120°F, or the demand for space heating is satisfied. Auxiliary space heating supplements solar energy for the perimeter zone.

Mode 4 - Domestic Hot Water Preheating: This mode is entered when solar hot water heating is desired and solar energy is available from the collectors. Solar energy is directed from the collector loop through the domestic hot water (DHW) recirculation loop to preheat hot water for DHW consumption. A high limit thermostat shuts off the flow to the DHW heat exchanger in the recirculation loop when the liquid temperature exceeds 180°F.

The air system has four modes of operation.

Mode 5 - Auxiliary Space Heating: This mode is entered when the collectors are inactive, the storage temperatures of both solar systems are below 85°F, and a demand for space heating exists. Circulation fan F3 supplies auxiliary energy from the furnace to the perimeter zone. Circulation continues in this mode until the demand for space heating is satisfied or solar energy is available from either the collectors, or storage.

Mode 6 - Collector-to-Storage: This mode is entered when two conditions are satisfied: first, the difference between the collector outlet temperature and the bottom of storage is greater than 14°F; secondly, there is no demand for space heating. Fan F1 circulates air from storage, through the collectors, and then back to storage. Circulation continues in this mode until the differential temperature is less than 4°F, or until a demand for space heating occurs. In this mode, motorized dampers

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Rademaker Corporation solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each component subsystem.

Each month a summary of overall performance of the Rademaker Corporation site and a detailed subsystem analysis are published. Monthly reports for the period covered by this System Performance Evaluation, October 1978 through March 1979, are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

D1, D3, D5, D6, D7 and D8 are closed, and motorized dampers D2 and D4 are open.

Mode 7 - Storage-to-Conditioned Space: This mode is entered when a demand for heating exists, the collector loop is inactive, and the top of rock thermal storage is above 85°F. Fan F1 circulates building return air through storage and supplies solar heated air to the space heating zone demanding heat. The solar control system determines which space heating zone is supplied with heat. Circulation continues in this mode until the storage temperature drops below 85°F, or the demand for space heating ceases. In this mode, motorized dampers D1, D5, D6 and D7 are opened, or closed, depending upon which area requires heat. For proper air circulation through storage, dampers D2 and D4 are closed, and D3 is opened.

Mode 8 - Collector-to-Conditioned Space: This mode is entered when two conditions are satisfied: first, a demand for space heating exists from the perimeter zone, interior zone, or warehouse; secondly, the differential temperature between the collector outlet and the bottom of rock thermal storage is greater than 14°F. Fan F1 circulates air from conditioned space through the collectors and supplies solar heated air to area demanding heat. The solar control system has a priority scheme that determines the order in which zone is supplied heat. Fans F3 and F4 assist in the air distribution. Circulation continues in this mode until the differential temperature between the collector outlet and the bottom of storage is less than 4°F, or the demand for space heating ceases. The auxiliary furnace supplements solar energy for the perimeter zone only. In this mode, motorized dampers D1, D5, D6 and D7 are either opened, or closed, as determined by heating requirements. To circulate air only through the collectors, motorized dampers D3, D4 and D8 are closed, and damper D2 is opened.

The liquid system and the air system operate independently, however, either system may be used in conjunction with the auxiliary furnace to satisfy a heating demand.

5. PERFORMANCE ASSESSMENT

The performance of the Rademaker Corporation solar energy system has been evaluated for the November 1978 through March 1979 time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load and the measured values for solar energy used and system solar fraction are presented. Also presented, where applicable, are the expected values for solar energy used and system solar fraction. The expected values have been derived from a modified f-chart* analysis which uses measured weather and subsystem loads as inputs. The model used in the analysis is based on manufacturers' data and other known system parameters. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level has been presented. The second view presents a more in-depth look at the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the space heating subsystem. Included in this area are all parameters pertinent to the operation of each individual subsystem.

The performance assessment of any solar energy system is highly dependent on the prevailing weather conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical weather parameters has been provided.

*f-chart is the designation of a procedure for designing solar heating systems. It was developed by the Solar Energy Laboratory, University of Wisconsin-Madison.

5.1. Weather Conditions

Average values of the daily incident solar energy in the plane of the collector array and the average outdoor temperature measured at the Rademaker Corporation site during the report period are presented in Tables 5.1-1 and 5.1-2.

Also presented are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from Reference Monthly Environmental Data for Systems in the National Solar Data Network [4]. A complete yearly listing of these values for the site is given in Appendix C.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are accumulated. Likewise, if a day's average temperature was 80°F, then 15 cooling degree-days are accumulated. The total number of heating and cooling degree-days are summed monthly.

During the six-month period from October 1978 through March 1979, a daily average of 1,028 Btu/ft^2 and 953 Btu/ft^2 of solar energy was incident on the liquid and air collector arrays, respectively. The difference is largely attributable to the difference in the tilt angle of each of the pyranometers which measure the incident solar energy. For the liquid and air collector arrays, the average measured daily average of incident solar energy was 7.4 percent lower than the long-term average. The measured average ambient temperature for the period was 40°F, which was two degrees below the long-term average of 42°F.

TABLE 5.1-1

LIQUID SYSTEM WEATHER CONDITIONS

Month	Daily Incident Solar Energy Per Unit Area (53° Tilt) (Btu/Ft^2-Day)		Ambient Temperature (°F)		Heating Degree-Days		Cooling Degree-Days	
	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average
Oct 78	1,351	1,424	54	58	360	246	5	23
Nov 78	907	1,051	47	45	525	612	0	0
Dec 78	1,026	829	37	36	864	915	0	0
Jan 79	809	887	26	33	1,208	995	0	0
Feb 79	1,003	1,099	29	36	1,018	832	0	0
Mar 79	1,069	1,260	48	44	540	673	3	10
Total	--	--	--	--	4,515	4,273	8	33
Average	1,028	1,092	40	42	753	712	1	6

TABLE 5.1-2

AIR SYSTEM WEATHER CONDITIONS

Month	Daily Incident Solar Energy Per Unit Area (33° Tilt) (Btu/Ft^2-Day)		Ambient Temperature (°F)		Heating Degree-Days		Cooling Degree-Days	
	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average
Oct 78	1,276	1,385	54	58	360	246	5	23
Nov 78	833	973	47	45	525	612	0	0
Dec 78	914	755	37	36	864	915	0	0
Jan 79	730	818	26	33	1,208	995	0	0
Feb 79	893	1,059	29	36	1,018	832	0	0
Mar 79	1,073	1,294	48	44	540	673	3	10
Total	--	--	--	--	4,515	4,273	8	33
Average	953	1,047	40	42	753	712	1	6

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and applied to the system load. The total system load is the sum of the energy requirements, both solar and auxiliary thermal, for each subsystem. The portion of the total load provided by solar energy is defined to be the solar fraction of the load. This solar fraction is the measure of performance for the solar energy system when compared to design or expected solar contribution.

The thermal performance of the Rademaker Corporation solar energy system is presented in Tables 5.2-1 through 5.2-6. This performance assessment is based on the six-month period from October 1978 through March 1979.

During the six-month reporting period, a total of 20.74 million Btu of solar energy was collected and the total system load was 63.07 million Btu. The measured amount of solar energy delivered to the space heating load was 9.30 million Btu. Because the domestic hot water subsystem was not instrumented, the solar energy extracted from the collected solar energy was identified as the difference between collected energy and the energy delivered to storage. The energy to the domestic hot water subsystem was 3.32 million Btu, an average of 0.55 million Btu per month. These data are included in the liquid system load and reflected in the combined system thermal performance.

The domestic hot water subsystem load accounted for 47 percent of the liquid system load. The solar fraction was 21 percent. The expected solar fraction of 32 percent was based on the inclusion of the domestic hot water load into the heating load. Since no instrumentation was available within the distribution part of the subsystem, the domestic hot water system and heating operating temperatures were the same in the load modeling of the expected solar fraction. The poor performance of the liquid system was caused in part by very low temperatures in December and January and by system problems which precluded a transfer of energy from storage to the load heat exchangers.

TABLE 5.2-1

COMBINED SYSTEM THERMAL PERFORMANCE

Month	Solar Energy Collected (Million Btu)	System Load (Million Btu)	Solar Energy Used (Million Btu)		Solar Fraction (Percent)	
			Expected	Measured	Expected	Measured
Oct 78	5.03	4.79	3.9	3.67	81	77
Nov 78	3.76	7.51	3.0	2.50	40	33
Dec 78	3.39	12.95	3.8	1.47	29	11
Jan 79	1.93	15.80	2.5	0.73	16	5
Feb 79	2.59	13.09	3.3	1.16	25	8.9
Mar 79	4.04	8.93	4.2	3.10	47	34.7
Total	20.74	63.07	20.7	12.63	--	--
Average	3.46.	10.51	3.5	2.11	33	20

TABLE 5.2-2

LIQUID SYSTEM THERMAL PERFORMANCE

Month	Solar Energy Collected (Million Btu)	System Load (Million Btu)	Solar Energy Used (Million Btu)		Solar Fraction (Percent)	
			Expected	Measured	Expected	Measured
Oct 78	3.28	2.97	2.30	2.21	77	74
Nov 78	2.46	4.13	1.50	1.44	37	35
Dec 78	2.34	6.81	2.00	0.59	30	9
Jan 79	1.46	8.05	1.20	0.35	15	4
Feb 79	1.93	6.78	1.70	0.62	25	9
Mar 79	2.47	4.77	2.00	1.88	42	39
Total	13.94	33.51	10.70	7.09	--	--
Average	2.32	5.59	1.78	1.18	32	21

TABLE 5.2-3

AIR SYSTEM THERMAL PERFORMANCE

Month	Solar Energy Collected (Million Btu)	System Load (Million Btu)	Solar Energy Used (Million Btu)		Solar Fraction (Percent)	
			Expected	Measured	Expected	Measured
Oct 78	1.75	1.82	1.6	1.46	100	81
Nov 78	1.30	3.38	1.5	1.06	44	32
Dec 78	1.05	6.14	1.8	0.88	30	15
Jan 79	0.47	7.75	1.3	0.38	17	7
Feb 79	0.66	6.31	1.6	0.54	25	11
Mar 79	1.57	4.16	2.2	1.22	52	31
Total	6.81	29.56	10.0	5.54	--	--
Average	1.14	4.93	1.67	0.92	34	19

TABLE 5.2-4

COMBINED SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

Month	Solar Energy System COP	Collector Array Subsystem COP	Space Heating Subsystem Solar COP
Oct 78	1.77	14.41	1.60
Nov 78	1.34	12.22	1.10
Dec 78	0.43	11.23	0.68
Jan 79	0.46	8.59	0.36
Feb 79	0.64	9.02	0.57
Mar 79	1.06	9.80	0.99
Total Period	0.95	11.02	0.88

TABLE 5.2-5

LIQUID SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

Month	Solar Energy System COP	Collector Array Subsystem COP	Space Heating Subsystem Solar COP
Oct 78	3.37	21.02	2.59
Nov 78	2.85	22.56	1.67
Dec 78	1.37	22.27	0.28
Jan 79	1.23	19.24	0.56
Feb 79	1.65	20.06	1.14
Mar 79	2.34	17.78	1.93
Total Period	2.14	20.46	1.36

TABLE 5.2-6

AIR SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

Month	Solar Energy System COP	Collector Array Subsystem COP	Space Heating Subsystem Solar COP
Oct 78	1.03	9.07	1.20
Nov 78	0.78	6.55	0.91
Dec 78	0.68	5.35	0.80
Jan 79	0.29	3.15	0.33
Feb 79	0.38	3.47	0.44
Mar 79	0.62	5.74	0.66
Total Period	0.62	5.67	0.72

The air system thermal performance was below expectations with a solar fraction of 19 percent. System problems included leaking motorized air dampers with the most serious problem being an apparent controller malfunction in the operation of perimeter zone motorized damper.

The combined system thermal performance gave a solar fraction of 20 percent which was significantly lower than the expected value of 33 percent, computed for the same weather conditions as actually experienced by each of the collector arrays.

The liquid and air systems both have direct and indirect (storage) modes of energy delivery to the common heating load. The direct delivery mode of the liquid system was not used, however leakage through the motorized valve which controls liquid flow from the collectors to heat exchanger HX4 permitted measureable energy transfer. The air system direct delivery mode from collector to load was controlled. The net performance of the two systems was such that the liquid system provided eight times the energy from storage that it did in the direct mode. The air system, conversely, delivered eight times as much energy to the load by the direct transfer of heated air than from storage.

The solar energy system COP (defined as the total solar energy to the load divided by the total solar energy system operating energy) was 4.79 for the six-month period. The collector array subsystem COP and the space heating subsystem COP were 11.02 and 12.35, respectively. The COP relates the amount of solar energy associated with various subsystems to the amount of electrical energy required to operate the solar portion of that subsystem. Since the electrical energy consumed by the domestic hot water subsystem was not instrumented, the domestic hot water load is not included in the solar energy system COP. Further breakdown of COP data is shown in Tables 5.2-4 through 5.2-6.

5.3 Subsystem Performance

The Rademaker Corporation solar energy installation may be divided into four subsystems:

1) Collector array
2) Storage
3) Hot water
4) Space heating.

Each subsystem is evaluated by the techniques defined in Section 4 and is numerically analyzed each month for the monthly performance reports. This section presents the results of integrating the monthly data available on the four subsystems for the period October 1978 through March 1979.

5.3.1 Collector Array Subsystem

Collector array performance is described by comparison of the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency which may be expressed as

$$\eta_c = Q_s/Q_i \quad (1)$$

where: η_c = Collector Array Efficiency (CAREF)

Q_s = Collected Solar Energy (SECA)

Q_i = Incident Solar Energy (SEA).

The gross collector array area is 240 square feet for the liquid system and the area is 185 square feet for the air system. The measured monthly values of incident solar energy, collected solar energy, and collector array efficiency are presented in Tables 5.3.1-1 and 5.3.1-2.

Evaluation of collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yields operational collector efficiency. Operational collector efficiency, η_{co}, is computed as follows:

$$\eta_{co} = Q_s / \left(Q_{oi} \times \frac{A_p}{A_a} \right) \quad (2)$$

where: Q_s = Collected Solar Energy (SECA)

Q_{oi} = Operational Incident Energy (SEOP)

A_p = Gross Collector Area (product of the number of collectors and the total envelope area of one unit) (GCA)

A_a = Gross Collector Array Area (total area perpendicular to the solar flux vector including all mounting, connecting and transport hardware (GCAA).

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

TABLE 5.3.1-1

LIQUID SYSTEM COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Oct 78	10.05	3.28	0.33	8.87	0.37
Nov 78	6.53	2.46	0.38	5.84	0.42
Dec 78	7.63	2.34	0.31	6.73	0.35
Jan 79	6.02	1.46	0.24	4.70	0.31
Feb 79	6.74	1.92	0.28	5.62	0.34
Mar 79	7.95	2.47	0.31	6.87	0.36
Total	44.92	13.94	--	38.63	--
Average	7.49	2.32	0.31	6.44	0.36

TABLE 5.3.1-2

AIR SYSTEM COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Oct 78	7.71	1.75	0.23	4.41	0.40
Nov 78	4.87	1.30	0.27	4.39	0.30
Dec 78	5.53	1.05	0.19	5.08	0.21
Jan 79	4.42	0.47	0.11	3.75	0.13
Feb 79	4.88	0.66	0.14	4.31	0.15
Mar 79	6.49	1.57	0.24	6.00	0.26
Total	33.89	6.81	--	27.95	--
Average	5.65	1.14	0.20	4.66	0.24

This latter efficiency term is not the same as collector efficiency as represented by the ASHRAE Standard 93-77 [5]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are also presented in Tables 5.3.1-1 and 5.3.1-2.

Collector array efficiency may be viewed from two perspectives. The first assumes that the efficiency be based upon all available solar energy; however, that point of view makes the operation of the control system a part of array efficiency. For example, energy may be available at the collector, but the collector fluid or air temperature is below the control minimum, thus the energy is not collected. The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Tables 5.3.1-1 and 5.3.1-2.

The second viewpoint assumes the efficiency be based upon only the incident energy during periods of collection. The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency." Efficiency computed by this method is used in the following discussion.

The Rademaker Corporation solar site has two collector arrays. The liquid system has an array of six flat-plate collectors, manufactured by Solar Development, Inc., with a gross area of 240 square feet. The air system array has 10 flat-plate collectors, manufactured by Solaron Corporation, with a gross area of 195 square feet. Tables 5.3.1-3 and 5.3.1-4 present a comparison of the actual performance of the collector arrays for the month of February 1979 against four predictions of performance which are based on instantaneous efficiency curves.

Table 5.3.1-3

ENERGY GAIN COMPARISON
(FEBRUARY)

SITE: RADEMAKER - LIQUID LOUISVILLE, KY

		ERROR			
		FIELD DERIVED			LAB
DAY	ACTUAL	MONTH	LONG TERM	2ND ORDER	PANEL
1	1.557E+05	0.018	-0.032	0.138	-0.189
2	1.344E+05	-0.001	-0.002	0.081	-0.201
3	0.000E+00	0.000	0.000	0.000	0.000
4	1.688E+05	0.004	0.003	0.072	-0.197
5	1.635E+05	0.029	-0.047	0.170	-0.183
6	2.717E+04	0.069	-0.244	-5.189	-0.168
7	1.507E+04	2.760	0.510	-1.278	1.661
8	3.199E+04	0.170	-0.228	-1.898	-0.098
9	1.419E+05	-0.366	-0.240	-0.190	-0.410
10	9.359E+04	-0.080	-0.178	0.411	-0.270
11	1.296E+05	-0.006	-0.038	0.139	-0.206
12	0.000E+00	0.000	0.000	0.000	0.000
13	1.401E+04	-0.045	-0.355	-1.751	-0.267
14	0.000E+00	0.000	0.000	0.000	0.000
15	0.000E+00	0.000	0.000	0.000	0.000
16	1.178E+05	0.038	0.017	0.197	-0.165
17	1.110E+05	-0.010	-0.124	0.443	-0.216
18	0.000E+00	0.000	0.000	0.000	0.000
19	1.162E+05	-0.047	-0.081	0.083	-0.239
20	8.866E+04	-0.045	-0.062	0.196	-0.237
21	9.179E+03	0.005	-0.348	0.328	-0.196
22	1.116E+04	3.496	0.017	-6.553	0.161
23	3.079E+04	-0.047	-0.052	0.274	-0.231
24	7.334E+02	0.537	0.570	0.518	0.254
25	0.000E+00	0.000	0.000	0.000	0.000
26	3.153E+04	0.048	-0.055	1.898	-0.163
27	1.969E+05	0.044	0.125	0.186	-0.160
28	6.428E+04	0.000	-0.032	0.394	-0.199
	1.853E+06	-0.016	-0.001	0.313	-0.215

CURVE	COEFFICIENTS			
	A0 (FRTA)	A1 (FRLL)	A2 (*)	R**2
PANEL	0.640	-0.630	N.A.	N.A.
MONTH	0.471	-0.500	N.A.	0.284
LT1ST	0.345	0.020	N.A.	0.000
LT2ND	0.085	2.610	-6.130	N.A.

Table 5.3.1-4

ENERGY GAIN COMPARISON
(FEBRUARY)

SITE: RADEMAKER - AIR LOUISVILLE, KY

		ERROR			
		FIELD DERIVED			LAB
DAY	ACTUAL	MONTH	LONG TERM	2ND ORDER	PANEL
1	6.524E+04	-0.040	0.385	-0.040	-0.473
2	5.792E+04	-0.096	0.068	-0.113	-0.497
3	0.000E+00	0.000	0.000	0.000	0.000
4	8.899E+04	0.049	0.135	0.004	-0.413
5	7.914E+04	0.048	0.441	0.062	-0.423
6	4.724E+03	-0.475	-6.455	-0.749	-0.728
7	3.848E+03	-28.516	-1.740	-0.855	7.415
8	4.160E+03	-0.236	-1.546	-0.886	-0.638
9	1.226E+04	0.444	-1.745	-0.771	-0.340
10	3.440E+04	-0.054	1.374	-0.464	-0.492
11	6.616E+04	-0.053	0.034	-0.122	-0.471
12	0.000E+00	0.000	0.000	0.000	0.000
13	2.679E+03	-0.416	-2.290	-0.800	-0.705
14	0.000E+00	0.000	0.000	0.000	0.000
15	0.000E+00	0.000	0.000	0.000	0.000
16	5.815E+04	0.040	0.329	0.001	-0.425
17	5.079E+04	-0.060	0.655	-0.174	-0.489
18	0.000E+00	0.000	0.000	0.000	0.000
19	4.094E+04	-0.413	-0.351	-0.395	-0.672
20	4.865E+04	-0.112	0.018	-0.195	-0.506
21	3.357E+03	-0.457	-4.464	-0.799	-0.720
22	5.758E+02	-0.687	-1.622	-0.889	-0.843
23	2.000E+04	0.096	0.361	-0.391	-0.393
24	0.000E+00	0.000	0.000	0.000	0.000
25	0.000E+00	0.000	0.000	0.000	0.000
26	9.470E+03	-0.221	0.062	-0.323	-0.571
27	1.066E+05	0.083	-0.027	-0.122	-0.385
28	3.927E+04	0.057	0.097	-0.296	-0.407
	7.972E+05	-0.044	0.259	-0.260	-0.473

CURVE	COEFFICIENTS			
	A0 (FRTA)	A1 (FRUL)	A2 (*)	R**2
PANEL	0.520	-0.630	N.A.	N.A.
MONTH	0.300	-0.420	N.A.	0.168
LTIST	0.403	-1.256	N.A.	0.700
LT2ND	0.430	-2.252	5.538	N.A.

Instantaneous efficiency curves are derived from laboratory test data supplied by the collector manufacturer and from three empirical sources: a linear regression line fit through field data obtained in February; a linear regression line fit through all field data in the base; and a curvilinear (second order) regression line fit through all field data in the base (the base data consists of all measurements relating to collector array performance made from October 1978 through March 1979.

Each error value presented in the error field of Tables 5.3.1-3 and 5.3.1-4 is computed by the equation

$$\text{error} = (A - P) / P \qquad (3)$$

where:

A is the actual energy gain of the collector array shown in column one (Million Btu/Day)

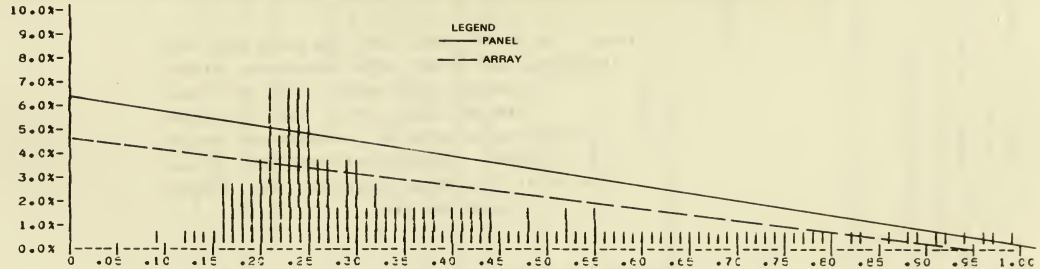
P is the predicted energy gain of the collector array based on projecting the measured operating point to the applicable instantaneous efficiency curve and multiplying by the measured insolation level and collector array area and then summing over all the measured operating points (Million Btu/Day).

The computed error is then a measure of how well the particular prediction curve fits the reality of dynamic operating conditions in the field.

Figures 5.3.1-1 and 5.3.1-2 present a histogram of the collector array operating points for February. Also presented are linear instantaneous efficiency curves based on controlled laboratory test data supplied by the collector manufacturer, field data for the month of February and long-term field data for the base period.

RADEMAKER - LIQUID LOUISVILLE, KY

COLLECTOR TYPE: SOLAR DEVELOPMENT COLLECTOR MODEL:



OPERATING POINT HISTOGRAM - FEBRUARY

FLUID PROPERTIES - FEBRUARY

PROPYLENE GLYCOL/WATER 45% BY VOLUME				
	COEFFICIENTS			
PROPERTY	A0	A1	A2	A3
SPECIFIC HEAT	8.524E-01	1.588E-04	1.092E-06	
DENSITY	8.604E+00	-2.008E-03	-5.197E-06	

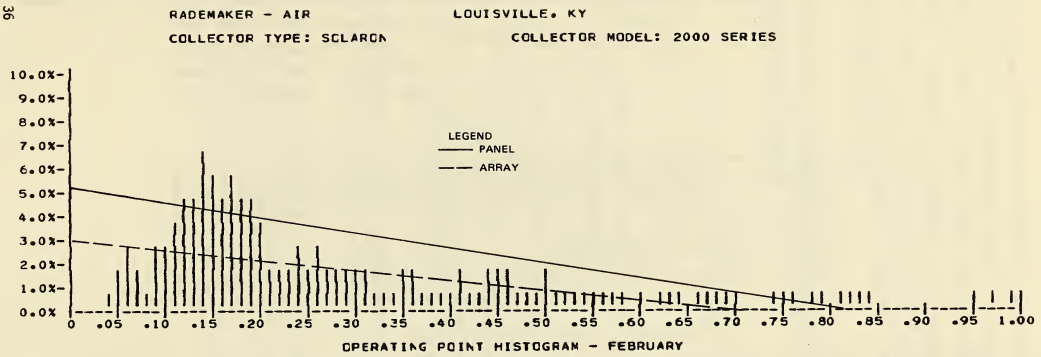
ARRAY FLOW RATE 4.64 GPM

PANEL FLOW RATE 0.81 GPM

AVERAGE TEMPERATURE GAIN 7.60 DEGR FAHRENHEIT

LONG TERM CURVE FIT VALID FROM 0.148 TO 0.363 .

Figure 5.3.1-1. COLLECTOR ARRAY OPERATING POINT HISTOGRAM AND INSTANTANEOUS EFFICIENCY CURVES



AIR PROPERTIES

AVERAGE LOCAL BAROMETRIC PRESSURE	14.50 PSI
AVERAGE LOCAL RELATIVE HUMIDITY	68.00
AVERAGE TEMPERATURE	46.70 DEGR FAHRENHEIT
ARRAY FLOW RATE	414.25 CUBIC FEET/MIN
PANEL FLOW RATE	82.85 CUBIC FEET/MIN
AVERAGE TEMPERATURE GAIN	18.09 DEGR FAHRENHEIT
LONG TERM CURVE FIT VALID FROM	0.042 TO 0.227 .

Figure 5.3.1-2. COLLECTOR ARRAY OPERATING POINT HISTOGRAM AND INSTANTANEOUS EFFICIENCY CURVES

The ordinate of the graph shown in Figures 5.3.1-1 and 5.3.1-2 has a printed range of 0 to 10 percent to display the distribution of collector array operating points. However, the value printed or the ordinate should be multiplied by 10 when the intercepts of the linear instantaneous efficiency curves are being evaluated (these values range from 0 to 100 percent).

The collector array operating points, X, are calculated each scan by the equation

$$X = (T_{f,i} - T_a) / I \qquad (4)$$

where:

$T_{f,i}$ is the inlet temperature of the collector array transport fluid (°F)

T_a is the temperature of the ambient air (°F)

I is the insolation rate ($Btu/Hr-Ft^2$).

Examination of the operating point histogram for the liquid system indicates that the predominant region of collector array operation occurred for operating points between 0.20 and 0.27 (45 percent of the time). This leads to the expectation that the operational collector array efficiency would typically be on the order of 34 percent, which is in agreement with the data presented in Table 5.3.1-3. The predicted panel performance is greater than the total array performance, however, the slope of each curve is approximately the same.

Reference to Figure 5.3.1-2 shows a less well behaved array performance. The operating point is centered at 0.15 and the array efficiency is approximately 25 percent. The collector array performance given in Table 5.3.1-2 shows the operational collector efficiency as 15 percent. The histogram data are based

on positive solar energy collected while the collected solar energy given in Table 5.3.1-2 is a net solar energy and is the positive solar energy collected less the energy which was sent to the collector array and dissipated. In the month of February, a malfunctioning motorized damper and air leakage through otherwise closed dampers allowed energy to be transferred from the office area to the collectors. The rejected energy was 0.64 million Btu. If the rejected energy is added to the net collected energy, the operational efficiency is 30 percent which is in better agreement with the array performance shown by the histogram.

In summary of collector performance, the liquid system array was operated normally and gave consistently good results. The air system collector array performance was below that expected. During the reporting period, manual intervention in the operation of the system as well as malfunctioning air flow diverters in the system ducting allowed solar and auxiliary energy from the loads to be dissipated through the collector array.

Additional information concerning collector array analysis in general may be found in a forthcoming paper [13] that describes collector array analysis procedures in detail and presents the results of analysis performed on numerous collector array installations across the United States.

5.3.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \quad (5)$$

where:

ΔQ = change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value) (STECH).

Q_{so} = energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium (STEO).

Q_{si} = energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium (STEI).

Evaluation of the system storage performance under actual transient system operation and weather conditions can be performed using the parameters listed above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the derivation presented below.

The overall thermal properties of the storage subsystem design can be derived empirically as a function of storage average temperature (average storage temperature for the reporting period) and the ambient temperature

in the vicinity of the storage tank (assumed to be ambient outdoor temperature since the storage tanks are in the warehouse area).

An effective storage heat transfer coefficient (C) for the storage subsystem can be defined as follows:

$$C = (Q_{si} - Q_{so} - \Delta Q_s)/[(\overline{T}_s - \overline{T}_a) \times t] \frac{Btu}{^{\circ}F\text{-}Hr} \qquad (6)$$

where:

C = effective storage heat transfer coefficient

Q_{si} = energy to storage (STEI)

Q_{so} = energy from storage (STEO)

ΔQ_s = change in stored energy (STECH)

$\overline{T}_s$ = storage average temperature (TS)

$\overline{T}_a$ = average ambient temperature in the vicinity of storage (TE)

t = number of hours in the month (HM).

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [6]. It has been calculated for each month in this report period and included, along with Storage Average Temperature, in Tables 5.3.2-1, 5.3.2-2 and 5.3.2-3.

It may be seen from Table 5.3.2-3 that the performance of the auxiliary 158 cubic foot rock thermal storage was very poor. It is suggested that no real attempt was made to utilize this storage nor to attempt a balance between the two available storage units. The air flow rate averaged approximately one twelfth the flow experienced through the

TABLE 5.3.2-1

LIQUID SYSTEM STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)	Effective Storage Heat Loss Coefficient (Btu/Hr-°F)
Oct 78	2.07	1.20	-0.11	0.53	98	29.84
Nov 78	1.50	0.61	-0.07	0.36	84	35.85
Dec 78	1.58	0	-0.05	0	84	46.67
Jan 79	1.09	0.07	0.03	0.09	77	26.09
Feb 79	1.43	0.26	0.03	0.21	79	33.84
Mar 79	1.62	1.20	-0.02	0.73	86	15.49
Total	9.29	3.34	-0.18	--	--	--
Average	1.55	0.56	-0.03	0.34	85	31.30

TABLE 5.3.2-2

AIR SYSTEM STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)	Effective Storage Heat Loss Coefficient (Btu/Hr-°F)
Oct 78	0.42	0.15	0	0.344	71	21.66
Nov 78	0.45	0.18	-0.05	0.280	69	20.45
Dec 78	0.16	-0.09	0	-0.561	64	12.74
Jan 79	0.12	-0.15	-0.01	-1.354	63	9.81
Feb 79	0.15	-0.09	0.02	-0.457	63	9.67
Mar 79	0.68	0.33	0.02	0.517	69	20.99
Total	1.98	0.33	-0.02	--	--	--
Average	0.33	0.06	0	0.16	67	15.89

TABLE 5.3.2-3

AIR SYSTEM AUXILIARY STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)	Effective Storage Heat Loss Coefficient (Btu/Hr-°F)
Oct 78	0.030	0	-0.01	11.16	70	3.36
Nov 78	0.036	0	-0.02	16.72	66	4.17
Dec 78	0.015	0.01	-0.01	5.32	60	1.05
Jan 79	0.013	0	-0.01	0	57	1.04
Feb 79	0.018	0	0.01	0	56	0.39
Mar 79	0.067	0	0.01	0	63	4.48
Total	0.18	0.01	-0.03	-	--	--
Average	0.03	0	-0.01	0	62	2.41

primary air rock storage. Average storage temperatures were too low to be effective in space heating. The heat loss coefficient of 2.41 is misleading because of the very low values of energy delivered to the storage bin and because the value for $\overline{T}_a$ was based on the measured outdoor temperature (the only instrumentation available). The temperature differential $\overline{T}_s - \overline{T}_a$ may have been quite different under the floor, in the warehouse and surrounding the rock storage bin.

Reference to Figure 3-1 shows that the air system has eight motorized dampers which control the air flow between the collectors, storage and the space heating load. During the reporting period, these motorized dampers were found to leak. Estimates were made of the energy diverted through the leaks to the conditioned heating areas and to the unconditioned warehouse area. No specific determination was attempted to differentiate between damper leaks and ducting leaks. In mid-November, the contractor modified dampers. Whenever there was a requirement for heat in the perimeter zone, motorized damper D1 opened regardless of the availability of solar energy. Consequently, air was drawn through the collectors and rock thermal storage. The return path of the air was through otherwise closed but leaking dampers. Energy (auxiliary and stored solar) was lost through the collectors to the environment and transferred to the warehouse. This particular problem persisted throughout the remainder of the reporting period. Reference to Table 5.3.2-2, air system storage subsystem performance, shows that from December through February, the average energy from storage was a negative value and in fact received energy from the intended load. Air was drawn from the office area, through the rock thermal storage, and through leaking dampers D3 and D4 by blower F3. Thermal energy was being transferred from the intended load to storage. This renders the efficiency of storage very low (16 percent) and makes the heat loss coefficient low, but more importantly, no longer a true indicator of the storage loss. For consistency, equation (6) was calculated with the negative energy from storage as observed.

The liquid system storage subsystem performance is given in Table 5.3.2-1. In the December and January time period a system malfunction (low water

level and pump/motor coupling problem) prevented energy transfer from storage. This is reflected in higher tank temperatures than expected and in very minimal energy output. The efficiency is accordingly low. Note that as in the air storage calculations, the values for $\overline{T}_a$ used in equation (6) are recorded outdoor temperatures since the storage tank is in the uncontrolled warehouse.

5.3.3 Hot Water Subsystem

Reference to Figure 3-1 will show that the hot water subsystem load was not instrumented to provide other than the energy extracted from the liquid collection loop. Table 5.3.3-1 gives the hot water load for each month of the reporting period.

TABLE 5.3.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Hot Water Load (Million Btu)
Oct 78	0.91
Nov 78	0.78
Dec 78	0.50
Jan 79	0.23
Feb 79	0.30
Mar 79	0.60
Total	3.32
Average	0.55

5.3.4 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy.

The performance of the Rademaker Corporation Liquid Space heating subsystem is presented in Table 5.3.4-1. For the six-month period from October 1978 through March 1979, the solar energy system supplied a total of 3.76 million Btu to the space heating load. The total heating load for this period was 30.16 million Btu, and the average monthly solar fraction was 12 percent.

The performance of the air space heating subsystem is presented in Table 5.3.4-2. The solar energy system supplied a total of 5.54 million Btu to the space heating load. The total heating load for this period was 29.56 million Btu, and the average monthly solar fraction was 19 percent.

Because the liquid and air systems solar energy contribution to the space heating load is in parallel with the auxiliary thermal energy source (furnace), the solar fraction of each system is a function of the auxiliary energy prorated to the subsystem. The schedule for proration is an equal contribution of auxiliary energy to liquid or air subsystems when both are contributing solar heating energy. Otherwise, the weighting is inversely proportional to the solar contribution to the space heating load of each subsystem. The heating load contribution was nearly equal for each subsystem, and the combined solar fraction was 16 percent. This is lower than the design expectation. Weather was not a significant factor. Solar energy from the liquid system came almost entirely from water thermal storage (factor of 8:1). Direct energy transfer resulted only from a leaking motorized valve, V4, (see Figure 3-1). The energy was used after insolation

TABLE 5.3.4-1

LIQUID HEATING SUBSYSTEM PERFORMANCE

Month	Space Heating Load (Million Btu)	Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Oct 78	2.05	1.29	0.76	0.92	63
Nov 78	3.35	0.66	2.69	4.85	20
Dec 78	6.31	0.09	6.22	10.95	1
Jan 79	7.82	0.12	7.70	14.62	2
Feb 79	6.48	0.31	6.16	11.71	5
Mar 79	4.17	1.28	2.88	5.40	31
Total	30.16	3.76	26.41	48.44	--
Average	5.03	0.63	4.40	8.07	12

TABLE 5.3.4-2

AIR HEATING SUBSYSTEM PERFORMANCE

Month	Space Heating Load (Million Btu)	Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Oct 78	1.82	1.46	0.36	0.88	81
Nov 78	3.38	1.06	2.32	4.61	32
Dec 78	6.14	0.88	5.26	10.35	15
Jan 79	7.75	0.38	7.37	14.48	7
Feb 79	6.31	0.54	5.77	11.69	11
Mar 79	4.16	1.22	2.94	6.19	31
Total	29.56	5.54	24.02	48.21	--
Average	4.93	0.92	4.00	8.03	19

was unavailable at night, in large part. For half of the reporting period, the energy was not transferred from the storage tanks because of a malfunction of the transfer pump P2 (Figure 3-1) and an abnormally low storage tank water level.

The air system solar fraction was better than the liquid system, and produced 47 percent more solar energy. The elapsed time in minutes for each mode of operation of the air system is given in Table 5.3.4-3, where:

Mode 0 = No solar operation
Mode 8 = Collector to load energy transfer
Mode 7 = Storage to load energy transfer
Mode 6 = Collector to storage energy transfer.

From these data, it is apparent from a comparison of Mode 7 to Mode 8 that the air system operates during the day in the direct mode, and that rock storage usage was limited. Whereas this is a time function, the energy transfer ratio of direct delivery to delivery from storage is 8:1, based on a total solar energy transfer to the load of 5.54 million Btu. In Mode 8, the direct energy transfer from the collector to the load mode, losses in ducting and in leaking dampers were a contribution to the low solar fraction. The greater loss was in Modes 6 and 7, where storage is involved. Losses included both solar and auxiliary energy being rejected through the collector in Mode 7, and losses from storage to the ambient warehouse temperature (unconditioned space) in Mode 6 and Mode 7.

TABLE 5.3.4-3

MODE DURATION

Month	Mode 0 (Minutes)	Mode 8 (Minutes)	Mode 7 (Minutes)	Mode 6 (Minutes)
Oct 78	35,048.27	2,856.69	730.93	6,003.91
Nov 78	32,069.64	3,667.10	1,478.28	5,984.77
Dec 78	34,767.76	6,644.02	418.34	2,809.66
Jan 79	37,185.42	5,093.69	277.98	2,082.72
Feb 79	30,049.76	6,382.73	1,037.42	2,849.91
Mar 79	27,970.00	4,670.09	2,795.81	9,203.90
Total	197,090.85	29,314.32	6,738.76	28,934.87
Average	32,848.48	4,885.72	1,123.13	4,822.48

5.4 Operating Energy

Operating energy for the Rademaker Corporation solar energy system is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Tables 5.4-1 and 5.4-2.

From Figure 3-1, it is apparent that the operating energy of air blower F1 can contribute to both the ECSS and to the load subsystems. During direct collector-to-load and collector-to-storage modes of operation the electrical operating energy of blower F1 is allocated to ECSS operating energy. During the storage-to-load mode the operating energy is counted as allocated to the space heating subsystem.

Recall that the solar collection was almost identical for liquid and air systems. However, the air system used 76 percent more operating energy than the liquid system during collection. The air system required 7.82 million Btu of electrical energy to provide space heating energy and the liquid system required only 3.74 million Btu. The total system operating energy was 4.42 million Btu and 9.02 million Btu for liquid and air systems, respectively.

TABLE 5.4-1

LIQUID SYSTEM OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Oct 78	0.16	0.52	0.68
Nov 78	0.11	0.53	0.64
Dec 78	0.11	0.64	0.74
Jan 79	0.08	0.59	0.67
Feb 79	0.10	0.59	0.69
Mar 79	0.14	0.88	1.02
Total	0.68	3.74	4.42
Average	0.11	0.62	0.74

TABLE 5.4-2

AIR SYSTEM OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Oct 78	0.19	1.04	1.23
Nov 78	0.20	1.09	1.29
Dec 78	0.20	1.24	1.43
Jan 79	0.15	1.38	1.53
Feb 79	0.19	1.32	1.51
Mar 79	0.27	1.75	2.02
Total	1.20	7.82	9.02
Average	0.20	1.30	1.50

5.5 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy. For consistency, the auxiliary source (fossil fueled furnace) is assumed to have a COP of 0.6. Liquid energy savings are presented in Table 5.5-1 and the air energy savings in Table 5.5-2. Fossil energy savings do not include considerations of the Domestic Hot Water subsystem, but include only the space heating subsystem. Net electrical savings are the negative of the energy required to operate both the ECSS and the space heating subsystems. Fossil equivalence at the source (Commercial Power Plant) is based on a fossil to electrical conversion efficiency of 30 percent and applies to the net electrical savings. The electrical energy savings for the Rademaker Corporation solar energy system include the operating energy of all pumps and blowers, except for motorized dampers which are outside of the furnace (see Figure 3-1). Additionally, part of the energy consumed by the furnace blower has been allocated as a penalty to the electrical energy savings. When the furnace is operating and supplying auxiliary thermal energy at the same time that solar energy is also being used, a portion of the furnace blower power is prorated to solar operating energy. When solar energy is satisfying the heating load and no auxiliary thermal energy is being used, the furnace blower operating energy is totally attributed to solar operating energy. Furthermore, the furnace blower power, when allocated to solar operating energy, is allocated in the ratio 0.3:0.7 to liquid and to air, respectively.

For the reporting period, the fossil savings were 21.07 million Btu at the expense of 10.77 million Btu of electrical energy. Assuming a dollar cost ratio between electrical and fossil of 3:1, there were no dollar cost savings for the reporting period.

TABLE 5.5-1

LIQUID ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)	Fossil Energy Savings (Million Btu)		Net Savings			Fossil Equivalent At Source (Million Btu)
				Electrical		Fossil	
	Space Heating	Hot Water	Space Heating	Million Btu	kwh	Million Btu	
Oct 78	-0.50	1.52	2.15	-0.65	-191.3	3.67	-2.17
Nov 78	-0.39	1.30	1.10	-0.50	-146.8	2.40	-1.67
Dec 78	-0.32	0.83	0.20	-0.43	-125.7	1.03	-1.43
Jan 79	-0.21	0.38	0.20	-0.29	- 84.1	0.58	-0.96
Feb 79	-0.28	0.50	0.52	-0.38	-109.9	1.02	-1.23
Mar 79	-0.67	1.00	2.13	-0.81	-235.9	3.13	-2.68
Total	-2.37	5.53	6.30	-3.05	-893.6	11.83	-10.16
Average	-0.40	0.92	1.05	-0.51	-148.9	1.97	-1.69

TABLE 5.5-2
AIR ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)	Fossil Energy Savings (Million Btu)	Net Savings			Fossil Equivalent At Source (Million Btu)
			Electrical		Fossil	
	Space Heating	Space Heating	Million Btu	kwh	Million Btu	
Oct 78	-1.22	2.43	-1.22	-356.6	2.43	-4.05
Nov 78	-1.16	1.76	-1.16	-339.9	1.76	-3.86
Dec 78	-1.09	1.47	-1.09	-320.5	1.47	-3.64
Jan 79	-1.17	0.64	-1.17	-341.9	0.64	-3.89
Feb 79	-1.23	0.90	-1.23	-361.3	0.90	-4.11
Mar 79	-1.85	2.04	-1.85	-542.9	2.04	-6.17
Total	-7.72	9.24	-7.72	-2,263.1	9.24	-25.72
Average	-1.29	1.54	-1.29	-377.2	1.54	-4.29

6. REFERENCES

1. U.S. Department of Energy, National Solar Data Network, Prepared under Contract Number EG-77-C-01-4049, by IBM Corporation, December, 1977.

2. J. T. Smok, V. S. Sohoni, J. M. Nash, "Processing of Instrumented Data for the National Solar Heating and Cooling Demonstration Program," Conference on Performance Monitoring Techniques for Evaluation of Solar Heating and Cooling Systems, Washington, D.C., April, 1978.

3. E. Streed, et. al., Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program, NBSIR 76-1137, National Bureau of Standards, Washington, August, 1976.

4. Mears, J. C. Reference Monthly Environmental Data for Systems in the National Solar Data Network. Department of Energy report SOLAR/0019-79/36. Washington, D.C., 1979.

5. ASHRAE Standard 93-77, Methods of Testing to Determine the Thermal Performance of Solar Collectors, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

6. ASHRAE Standard 94-77, Methods of Testing Thermal Storage Devices Based on Thermal Performance, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

7. * Monthly Performance Report, Rademaker Corporation, SOLAR/2009-78/10, Department of Energy, Washington (October 1978).

8. * Monthly Performance Report, Rademaker Corporation, SOLAR/2009-78/11, Department of Energy, Washington (November 1978).

9. * Monthly Performance Report, Rademaker Corporation, SOLAR/2009-78/12, Department of Energy, Washington (December 1978).

10. * Monthly Performance Report, Rademaker Corporation, SOLAR/2009-79/01, Department of Energy, Washington (January 1979).

11. * Monthly Performance Report, Rademaker Corporation, SOLAR/2009-79/02, Department of Energy, Washington (February 1979).

12. * Monthly Performance Report, Rademaker Corporation, SOLAR/2009-79/03, Department of Energy, Washington (March 1979).

*Copies of these reports may be obtained from Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

13. McCumber, W. H. Jr., "Collector Array Performance for Instrumented Sites of the National Solar Heating and Cooling Demonstration Program," to be published and distributed at the 1979 Solar Update Conference.

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework, which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HSVE) is the estimated difference between the electrical energy requirements of an alternative

conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.

- WIND SPEED (WIND) is the average wind speed measured at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR THE RADEMAKER CORPORATION SITE

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by:

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{IOOl} \times \text{AREA}] \times \Delta\tau$$

where IOOl is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [M100 \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \bar{C}_p\ \Delta T$$

where $\bar{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60) \Sigma [EP100] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts, and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

LIQUID SYSTEM

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

AVERAGE AMBIENT TEMPERATURE (°F)

$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$

AVERAGE BUILDING TEMPERATURE (°F)

$TB = (1/60) \times \Sigma\ T600 \times \Delta\tau$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$SEOP = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$

WHEN THE COLLECTOR LOOP IS ACTIVE

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD\ (T_2, T_1) = \int_{T_1}^{T_2} C_p\ (T)\ \Delta T$$

THIS FUNCTION COMPUTES THE ENTHALPY CHANGES OF WATER AS IT PASSES THROUGH A HEAT EXCHANGING DEVICE

SOLAR ENERGY TO STORAGE (BTU)

$STEI = \Sigma\ [M400 \times HWD\ (T151, T101)] \times \Delta\tau$

COLLECTED SOLAR ENERGY (BTU/FT^2)

$SEC = \Sigma\ [M100 \times CP \times (T150 - T100)] \times \Delta\tau$

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HSE = \Sigma\ [M100 \times CP \times (T452 - T100) + M400 \times HWD\ (T400 - T450)] \times \Delta\tau$

SOLAR ENERGY FROM STORAGE (BTU)

$STEO = \Sigma [M400 \times HWD (T400, T450)] \times \Delta\tau$

AVERAGE TEMPERATURE OF STORAGE (°F)

$TST = (1/60 \times \Sigma [(T200 + T202)/2] \times \Delta\tau$

ECSS OPERATING ENERGY (BTU)

$CSOPE = 56.8833 \times \Sigma EP101 \times \Delta\tau$

SOLAR ENERGY TO DOMESTIC HOT WATER SUBSYSTEM (BTU)

$HWSE = \Sigma [M100 \times (T150 - T151)] \times \Delta\tau$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$HOPE = 56.8833 \times \Sigma [EP400 + 0.3 \times EP402] \times \Delta\tau$

SPACE HEATING AUXILIARY THERMAL ENERGY (BTU)

$HAT = HSE_A/(HSE_A + HSE) \times HAT_T$

WHERE SUBSCRIPT $_A$ = AIR SUBSYSTEM AND $_T$ = TOTAL

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$SEA = CLAREA \times SE$

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$SECA = CLAREA \times SEC$

SPACE HEATING AUXILIARY FOSSIL ENERGY (BTU)

$HAF = HSE_A/(HSE_A + HSE) \times HAF_T$

CHANGE IN STORED ENERGY (BTU)

$STECH = K \times (STOTP - STOTP_P)$

WHERE THE SUBSCRIPT $_P$ REFERS TO A PRIOR REFERENCE VALUE AND K IS THE STORAGE ENERGY

ENERGY DELIVERED TO LOAD SUBSYSTEMS FROM ECSS (BTU)

$CSEO = HWSE + HSE$

STORING EFFICIENCY

$STEFF = (STECH + STEO)/STEI$

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

SPACE HEATING LOAD (BTU)

HL = HSE + HAT

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = 56.8833 x Σ (EP400 + 0.3 * EP402) $\Delta\tau$

SYSTEM LOAD (BTU)

SYSL = HL

SOLAR ENERGY TO LOAD (BTU)

SEL = HWSE + HSE

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

SPACE HEATING SOLAR FRACTION (PERCENT)

HSFR = 100 x (HSE/HL)

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

SFR = HSFR

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HAT

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HOPE + CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXF + SECA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HSVE - CSOPE

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXF + SYSOPE x 3)

AUXILIARY FOSSIL ENERGY TO LOADS (BTU)

AXF = HAF

SPACE HEATING SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

HSVF = HSE/0.6

TOTAL FOSSIL ENERGY SAVINGS (BTU)

TSVF = HSVF

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

AIR SYSTEM

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

AVERAGE AMBIENT TEMPERATURE (°F)

$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$

AVERAGE BUILDING TEMPERATURE (°F)

$TB = (1/60) \times \Sigma\ T600 \times \Delta\tau$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$SE = (1/60) \times \Sigma\ I002 \times \Delta\tau$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$SEOP = (1/60) \times \Sigma\ [I002 \times CLAREA] \times \Delta\tau$

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

$HRF = 0.24 + 0.444 \times HR$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO OF THE TRANSPORT AIR. THIS FUNCTION IS USED WHENEVER THE HUMIDITY RATIO WILL REMAIN CONSTANT AS THE TRANSPORT AIR FLOWS THROUGH A HEAT EXCHANGING DEVICE.

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$SECA = \Sigma\ [M103 \times HRF \times (T153 - T103)] \times \Delta\tau$

SOLAR ENERGY TO STORAGE (BTU)

$STEI = \Sigma\ [M401 \times HRF \times (T451 - T401) + M403\ (T453 - T403)] \times \Delta\tau$

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HSE = \Sigma\ [M401 \times HRF \times (T451 - T401) + M403\ (T453 - T403) + (M103 - M401 - M403)(T153 - T458)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE (BTU)

$$STEO = \Sigma\ [(M401 \times HRF \times (T451 - T401) + M402 \times (T453 - T403)] \times \Delta\tau$$

WHEN THE COLLECTOR BLOWER IS OFF AND THE AIR HANDLER BLOWER IS ON

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TST = (1/60) \times \Sigma\ [(T203 + T205 + T206 + T207)/4] \times \Delta\tau$$

ECSS OPERATING ENERGY (BTU)

$$CSOPE = 56.8833 \times \Sigma\ EP100 \times \Delta\tau$$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$$HOPE = 56.8833 \times \Sigma\ [0.7 \times EP402] \times \Delta\tau$$

SPACE HEATING AUXILIARY THERMAL ENERGY (BTU)

$$HAT = HAT_T - HAT_L$$

COLLECTED SOLAR ENERGY (BTU)

$$SEC = SECA/CLAREA$$

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$$SEA = CLAREA \times SE$$

SPACE HEATING AUXILIARY FOSSIL ENERGY (BTU)

$$HAF = HAF_T - HAF_L$$

CHANGE IN STORED ENERGY (BTU)

$$STECH = K \times (STOTP - STOTP_p)$$

WHERE THE SUBSCRIPT $_p$ REFERS TO A PRIOR REFERENCE VALUE AND K IS THE ENERGY IN STORAGE BINS

ENERGY DELIVERED TO LOAD SUBSYSTEMS FROM ECSS (BTU)

$$CSEO = HSE$$

STORING EFFICIENCY

$$STEFF = (STECH + STEO)/STEI$$

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

SPACE HEATING LOAD (BTU)

HL = HSE + HAT

SPACE HEATING SYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = 56.8833 x 0.7 x Σ EP402 $\Delta\tau$

SYSTEM LOAD (BTU)

SYSL = HL

SOLAR ENERGY TO LOAD (BTU)

SEL = HSE

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

SPACE HEATING SOLAR FRACTION (PERCENT)

HSFR = 100 x (HSE/HL)

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

SFR = HSFR

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HAT

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HOPE + CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXF + SECA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HSVE - CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXF + SECA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HSVE - CSOPE

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXF + SYSOPE x 3.33)

AUXILIARY FOSSIL ENERGY TO LOAD (BTU)

AXF = HAF

SPACE HEATING SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

HSVF = HSE/0.6

TOTAL FOSSIL ENERGY SAVINGS (BTU)

TSVF = HSVF

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

SITE: RADEMAKER 8. LOCATION: LOUISVILLE KY

ANALYST: J. THOMAS FDRIVE NO.: 38.

COLLECTOR TILT: 53.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 38.20 (DEGREES) RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1423.	546.	0.38350	1.625	887.	995	0	33.
FEB	1880.	789.	0.41969	1.393	1099.	832	0	36.
MAR	2463.	1102.	0.44752	1.143	1260.	673	10	44.
APR	3060.	1467.	0.47949	0.929	1363.	302	11	56.
MAY	3473.	1722.	0.49582	0.796	1370.	106	97	65.
JUN	3637.	1902.	0.52307	0.739	1407.	8	248	73.
JUL	3549.	1836.	0.51736	0.763	1402.	0	347	77.
AUG	3214.	1681.	0.52307	0.870	1462.	0	313	76.
SEP	2675.	1361.	0.50860	1.066	1450.	40	148	69.
OCT	2048.	1043.	0.50947	1.364	1424.	246	23	58.
NOV	1528.	653.	0.42701	1.610	1051.	612	0	45.
DEC	1297.	487.	0.37529	1.704	829.	915	0	36.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

SITE: RADEMAKER 8. LOCATION: LOUISVILLE KY

ANALYST: J. THOMAS FDRIVE NO.: 38.

COLLECTOR TILT: 33.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 38.20 (DEGREES) RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1423.	546.	0.38350	1.499	818.	995	0	33.
FEB	1880.	789.	0.41969	1.342	1059.	832	0	36.
MAR	2463.	1102.	0.44752	1.173	1294.	673	10	44.
APR	3060.	1467.	0.47949	1.027	1507.	302	11	56.
MAY	3473.	1722.	0.49582	0.931	1604.	106	97	65.
JUN	3637.	1902.	0.52307	0.890	1694.	8	248	73.
JUL	3549.	1836.	0.51736	0.908	1668.	0	347	77.
AUG	3214.	1681.	0.52307	0.986	1658.	0	313	76.
SEP	2675.	1361.	0.50860	1.124	1529.	40	148	69.
OCT	2048.	1043.	0.50947	1.328	1385.	246	23	58.
NOV	1528.	653.	0.42701	1.491	973.	612	0	45.
DEC	1297.	487.	0.37529	1.552	755.	915	0	36.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

U.S. GOVERNMENT PRINTING OFFICE: 1979-0-676-019/13

UNIVERSITY OF FLORIDA
3 1262 07122 4256